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U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Environmental Satellite Service

Vertical Resolution of Temperature Profiles for High Resolution Infrared Radiation Sounder (HIRS)

Y. M. CHEN
H. M. WOOLF
W. L. SMITH

WASHINGTON, D.C.
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VERTICAL RESOLUTION OF TEMPERATURE PROFILES FOR HIGH RESOLUTION INFRARED RADIATION SOUNDER (HIRS)

Y. M. Chen*, H. M. Woolf and W. L. Smith
National Environmental Satellite Service
National Oceanic and Atmospheric Administration
Washington, D. C.

ABSTRACT. By using the method of Backus and Gilbert, the intrinsic vertical resolution of temperature profiles obtained from the High Resolution Infrared Radiation Sounder (HIRS) on the Nimbus-F satellite, which contains channels in both 4.3-μm and 15-μm CO_2 absorption bands, is evaluated and compared with those of channels in the 4.3-μm band and the 15-μm band alone. It is found that the combination of 4.3-μm and 15-μm bands is superior to the other two cases for all levels of the pressure.

1. INTRODUCTION

One of the basic problems in atmospheric temperature profile inversion techniques is the intrinsic vertical resolution of the measurement system. Recently, the fundamental technique for obtaining a direct quantitative value in answer to the problem was developed by Backus and Gilbert (1968, 1970) for the analysis of the solid earth. Conrath (1971) has applied it to the problem of the vertical sounding of the atmosphere by means of remote radiation measurements (with random noise) in the 15-μm CO_2 absorption band.

The purposes of this paper are to evaluate the intrinsic vertical resolution of temperature profiles obtained from the High Resolution Infrared Sounder (HIRS) on the Nimbus-F satellite (which contains channels in both 4.3-μm and 15-μm CO_2 absorption bands) and to compare it with those obtained separately in the 4.3-μm and 15-μm bands. First, a brief review of the formulation of Backus and Gilbert is presented. Then for various levels of atmospheric pressure p, the averaging kernel A(x,x'), the center of A(x,x'), and the resolving length of A(x,x') are computed and plotted as functions of p for three individual cases, the 4.3-μm band, the 15-μm band and the 4.3-μm + 15-μm bands (HIRS). Finally, we discuss and compare these three cases.

2. THE METHOD OF BACKUS AND GILBERT

In the remote sensing of atmospheric temperature profiles, measurements are made of radiances in a finite number of spectral intervals within

*Permanent address: Department of Applied Mathematics and Statistics
State University of New York, Stony Brook, New York 11790

atmospheric absorption bands. For a nonscattering atmosphere in local thermodynamic equilibrium, the expression for the radiances has the form

$$I(\nu_i) = B\left[T(p_o),\nu_i\right]\tau(p_o,\nu_i) - \int_{x(o)}^{x(p_o)} B\left[T(p),\nu_i\right]\frac{d\tau(p,\nu_i)}{dx(p)}\,dx(p)\,, \qquad (1)$$

$$i = 1, 2,\ldots, m\,,$$

where $B[T(p),\nu]$ is the Planck function for temperature $T(p)$ at pressure p; the independent variable x can be any monotonic function of p ($x = \ln p$ being used here); p_o is the surface pressure; and $\tau(p,\nu_i)$ is the transmittance of the atmosphere above pressure p at ν_i.

The inversion problem then is to estimate the temperature profile $T(p)$, given the atmospheric transmittances $\tau(p,\nu_i)$ and measurements of the radiances $\{I(\nu_i)\}$, $i = 1, 2,\ldots, m$. If the contribution from the nonlinearity of eq (1) is small, then only the first iteration of the iterative algorithm of Chen (1973) or the procedure of Backus and Gilbert will be sufficient for our purpose. Hence, the contribution from nonlinearity is assumed to be small throughout.

Let

$$T(p) \cong T_o(p) + \delta T(p)\,, \qquad (2)$$

where $T_o(p)$ is the reference profile and is taken to be the U.S. Standard Atmosphere. Then from Chen (1973), $\delta T(p)$ should be the best approximate solution of the linearized equation

$$\int_{-\infty}^{x_o} K\left[x,\nu_i\right]\,\delta T(x)\,dx = \delta I(\nu_i)\,, \quad i = 1, 2,\ldots, m, \qquad (3)$$

where $$K\left[x,\nu_i\right] \equiv \left.\frac{d\,B\left[T(x),\,\nu_i\right]}{d\,T}\right|_{T_o}\frac{d\tau(x,\nu_i)}{dx}\,, \qquad (4)$$

$$\delta I(\nu_i) \equiv B\left[T_o(x_o),\,\nu_i\right]\tau(x_o,\nu_i) - \int_{-\infty}^{x_o} B\left[T_o(x),\nu_i\right]\frac{d\tau(x,\nu_i)}{dx}\,dx - I(\nu_i), \qquad (5)$$

and dB/dT is the Fréchet derivative of $B[T]$.

The weighted average of δT at x which gives heavy emphasis to points close to x and very little to distant points is defined by

$$\langle\delta T\rangle_x = \int_{-\infty}^{x_o} A(x,x')\,\delta T(x')\,dx'\,, \qquad (6)$$

where the averaging kernel A is normalized according to

$$\int_{-\infty}^{x_o} A(x,x')\ dx' = 1 . \tag{7}$$

$\langle \delta T \rangle_x$ is the most localized weighted average if and only if the averaging kernel A closely resembles the Dirac delta function $\delta(x'-x)$. The spread of A from x is defined by

$$Q(x, A) \equiv \alpha_J \int_{-\infty}^{x_o} J(x,x')\ A^2(x,x')\ dx' , \tag{8}$$

where J(x,x') is a chosen infinitely differentiable function of x' such that J(x,x) = 0 and increases monotonically as x' increases or decreases away from x with dimension of x'^2, and

$$\alpha_J \equiv \frac{\ell}{\int_{-\infty}^{x_o} J(x,x')\ A_\ell^2(x,x')\ dx'} \tag{9}$$

$$\text{with} \quad A_\ell(x,x') \equiv \begin{cases} 1/\ell , & x - \ell/2 < x' < x + \ell/2 , \\ 0, & |x' - x| \geq \ell/2 , \end{cases} \tag{10}$$

$$\text{Note that} \quad Q(x, A_\ell) = \ell \quad (\text{the spread of } A_\ell). \tag{11}$$

If A has a sharp peak, the choice of J is rather free. However, if A has a blurred peak, the selection of J is much more critical. Throughout,

$$J(x,x') = (x - x')^2 \tag{12}$$

is used. ($\alpha_J = 12.$) As one will see later, this choice of J is not very good for 4.3-μm CO_2 channels in the upper stratosphere ($p \cong 8 - 60$ mb).

Equation (3) shows that $\{\delta I(\nu_i)\}$, i = 1,2,...,m, are m bounded linear functionals of $\delta T(x)$. Since $\langle \delta T \rangle_x$ and $\{\delta I(\nu_i)\}$, i = 1,2,...,m, all depend linearly on the function δT, it follows that $\langle \delta T \rangle_x$ must depend linearly on $\{\delta I(\nu_i)\}$. Therefore, there should exist constants $\{a_i(x)\}$, i = 1,2,...,m, depending on the fixed point x such that

$$\langle \delta T \rangle_x = \sum_{i=1}^{m} a_i(x)\ \delta I(\nu_i) . \tag{13}$$

Hence from (3) and (6),

$$A(x,x') = \sum_{i=1}^{m} a_i(x)\ K[x', \nu_i] . \tag{14}$$

It follows from (8) and (14) that Q(x, A) is a positive-definite quadratic function of $\{a_i(x)\}$. Since the determination of the most localized weighted

average $\langle \delta T \rangle_x$ is equivalent to minimizing the spread of A from x, subject to the constraint (7), by using the method of Lagrange multipliers, the proper set of $\{a_i(x)\}$ satisfies the following set of m+1 linear algebraic equations:

$$\left.\begin{aligned} \sum_{j=1}^{m} \left\{ 12 \int_{-\infty}^{x_o} (x-x')^2 K\left[x',\nu_i\right] K\left[x',\nu_j\right] dx' \right\} a_j(x) + \lambda \int_{-\infty}^{x_o} K\left[x',\nu_i\right] dx' = 0, \\ i = 1,2,\ldots,m, \\ \sum_{j=1}^{m} \left\{ \int_{-\infty}^{x_o} K\left[x',\nu_j\right] dx' \right\} a_j(x) = 1 , \end{aligned}\right\} \quad (15)$$

where λ is a Lagrange multiplier.

The vertical resolution of the temperature profile at the level x obtainable from a given set of radiance measurements is determined by the closeness of A(x,x') to $\delta(x' - x)$. Visually, the plot of A (x,x') vs. x' gives a qualitative estimate of the vertical resolution at x. To characterize the behavior of A(x,x') more precisely, the "resolving length" of A(x,x') is introduced and defined as the spread about its center,

$$w(x) = 12 \int_{-\infty}^{x_o} \left[c(x) - x'\right]^2 A^2(x,x') \, dx' , \quad (16)$$

where

$$c(x) = \int_{-\infty}^{x_o} x' \, A^2(x,x') \, dx' \Big/ \int_{-\infty}^{x_o} A^2(x,x') \, dx' \quad (17)$$

is the "center" of A(x,x').

3. APPLICATION TO HIRS

The method of Backus and Gilbert has been applied to an analysis of the vertical resolution of temperature profiles inferred from radiance measurements in two CO_2 absorption bands observed by the High Resolution Infrared Radiation Sounder (HIRS). The 7 channels in the 15-μm CO_2 band and the 5 channels in the 4.3-μm CO_2 band in the study are listed in table 1. The $d\tau_i/dx(p)$ vs. p curves for 15-μm and 4.3-μm CO_2 bands are shown in figures 1 and 2 respectively. Similarly, the $dB_i/dT\big|_{T_o} . d\tau_i/dx(p)$ radiative transfer kernels vs. p for 15-μm and 4.3-μm CO_2 bands are shown in figure 3. The averaging kernel A for each of various pressure levels, ranging from 1 mb to 1000 mb, is computed for 3 separate cases: the 5 channels in the 4.3-μm band alone, the 7 channels in the 15-μm band alone, and the 12 channels in the combination of 4.3-μm and 15-μm bands. The corresponding set of three averaging kernels at various levels of p are plotted as functions of atmospheric pressure in figures 4 to 12. These curves give a qualitative estimate of the vertical resolution at the indicated levels and offer a visual comparison for the resolving length and the center of A(x,x') among the

Table 1.--HIRS channel spectral characteristics

CO_2 band	Channel no.	Center frequency (cm^{-1})
15 μm	1	668.5
	2	680.0
	3	690.0
	4	703.0
	5	716.0
	6	733.0
	7	749.0
4.3 μm	11	2190.0
	12	2210.0
	13	2240.0
	14	2270.0
	15	2360.0

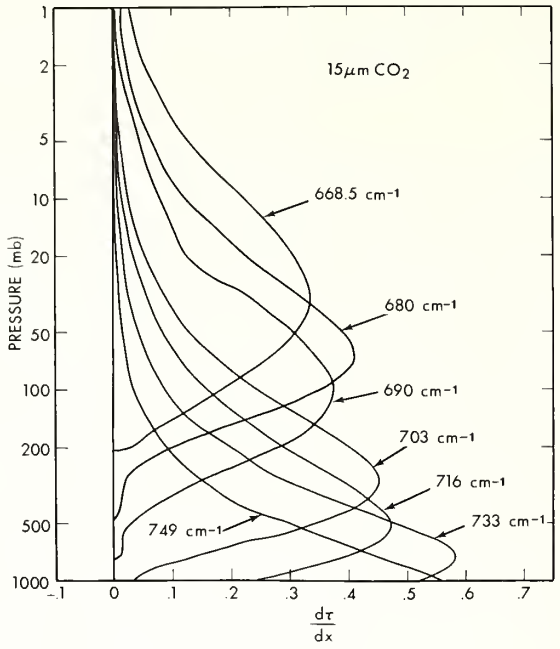

Figure 1.--*The derivative of transmittance with respect to the logarithm of pressure for the 15-μm CO_2 absorption band.*

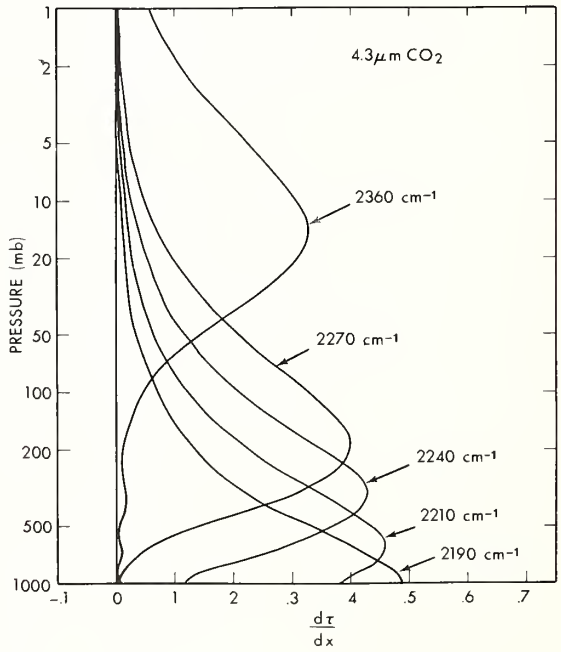

Figure 2.--*The derivative of transmittance with respect to the logarithm of pressure for the 4.3-μm CO_2 absorption band.*

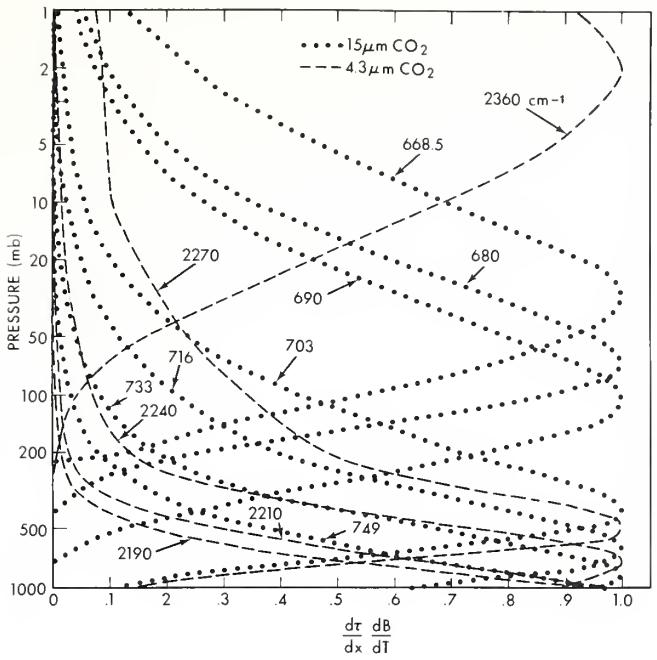

Figure 3.--*Radiative transfer kernels for the 15-μm and 4.3-μm CO_2 absorption bands vs. pressure.*

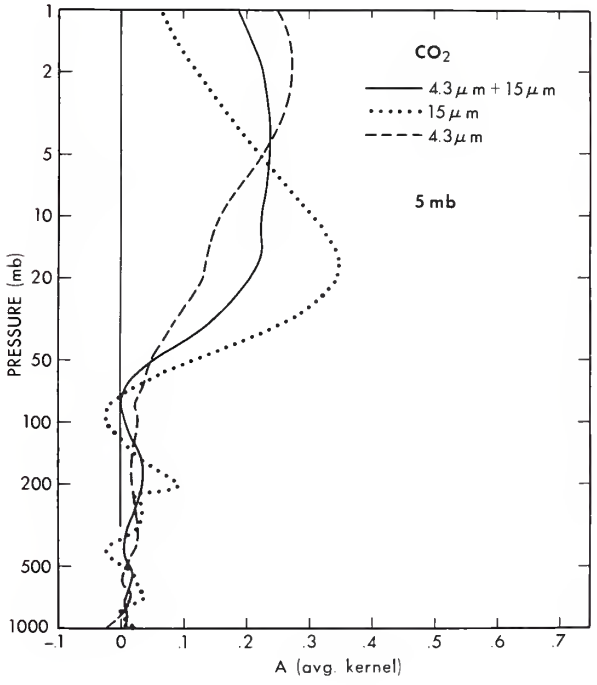

Figure 4.--*Averaging kernels at 5 mb for the 4.3-μm band, 15-μm band and 4.3-μm + 15-μm bands plotted as functions of atmospheric pressure.*

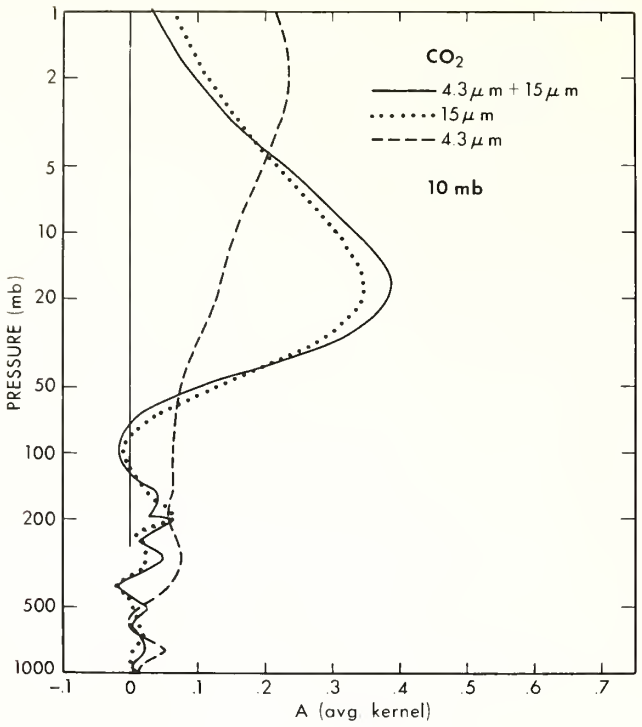

Figure 5.--*Averaging kernels at 10 mb for the 4.3-μm band, 15-μm band, and 4.3-μm + 15-μm bands plotted as functions of atmospheric pressure.*

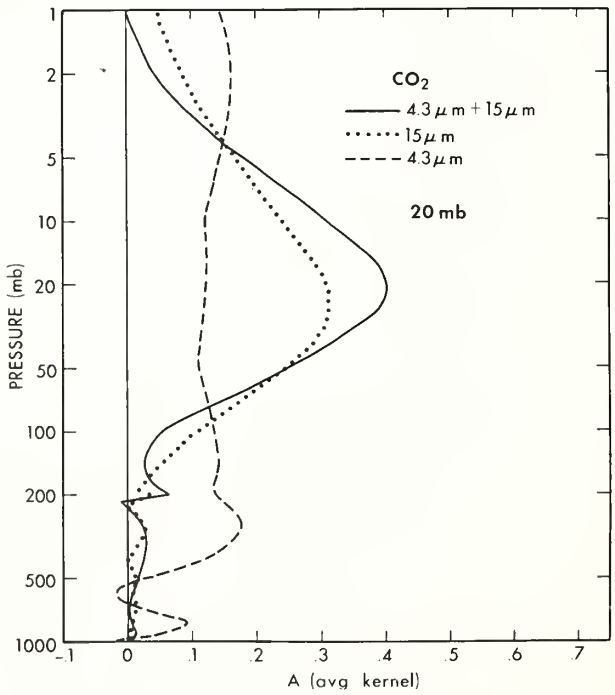

Figure 6.--*Averaging kernels at 20 mb for the 4.3-μm band, 15-μm band, and 4.3-μm + 15-μm bands plotted as functions of atmospheric pressure.*

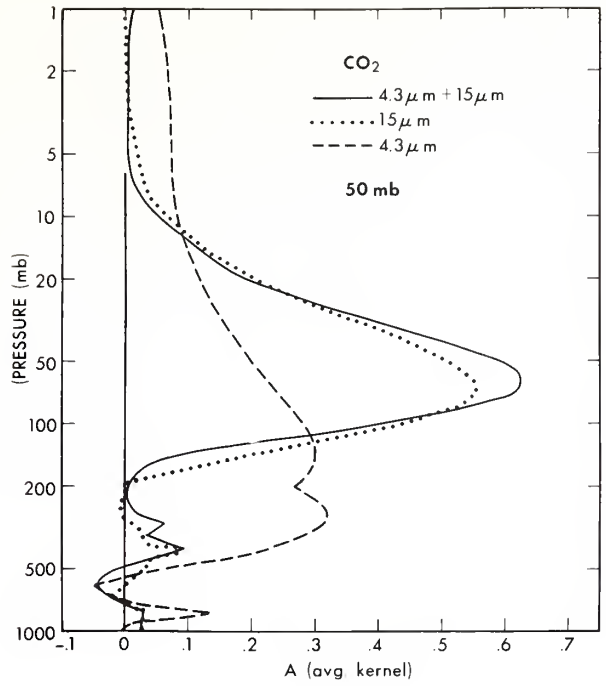

Figure 7.--*Averaging kernels at 50 mb for the 4.3-μm band, 15-μm band, and 4.3-μm + 15-μm bands plotted as functions of atmospheric pressure.*

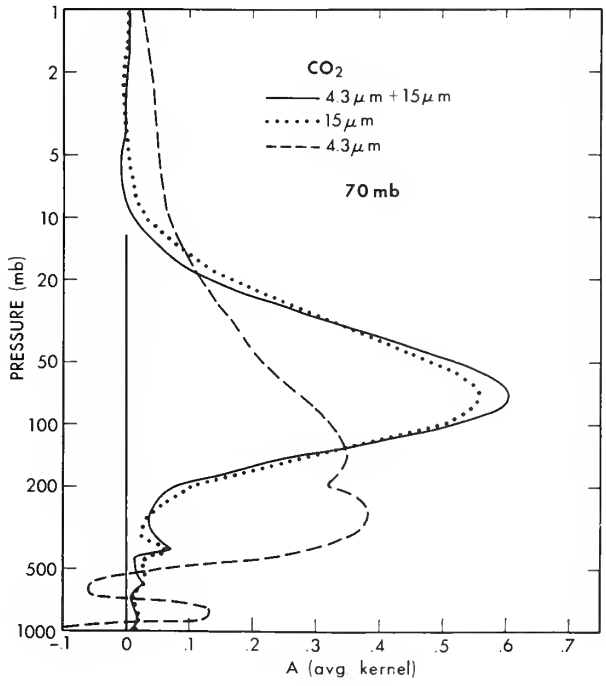

Figure 8.--*Averaging kernels at 70 mb for the 4.3-μm band, 15-μm band, and 4.3-μm + 15-μm bands plotted as functions of atmospheric pressure.*

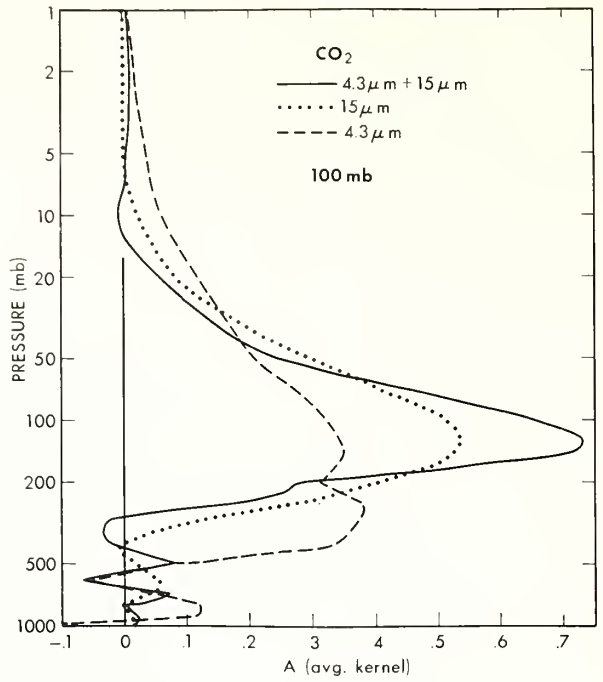

Figure 9.--*Averaging kernels at 100 mb for the 4.3-μm band, 15-μm band, and 4.3-μm + 15-μm bands plotted as functions of atmospheric pressure.*

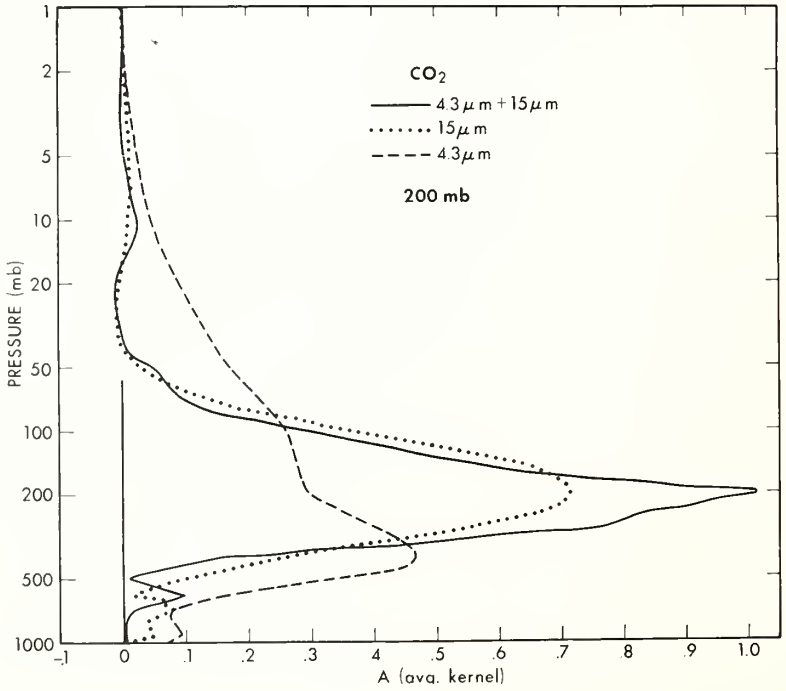

Figure 10.--*Averaging kernels at 200 mb for the 4.3-μm band, 15-μm band, and 4.3-μm + 15-μm bands plotted as functions of atmospheric pressure.*

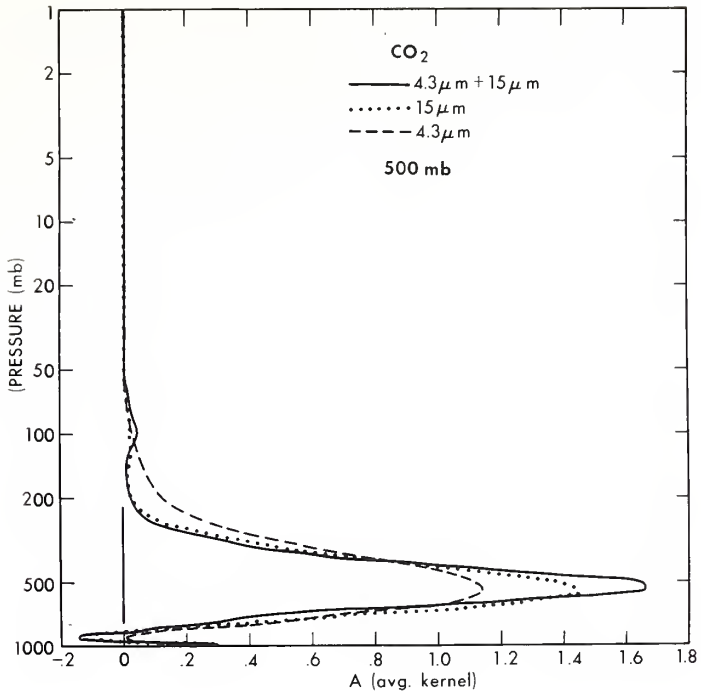

Figure 11.--*Averaging kernels at 500 mb for the 4.3-μm band, 15-μm band, and 4.3-μm + 15-μm bands plotted as functions of atmospheric pressure.*

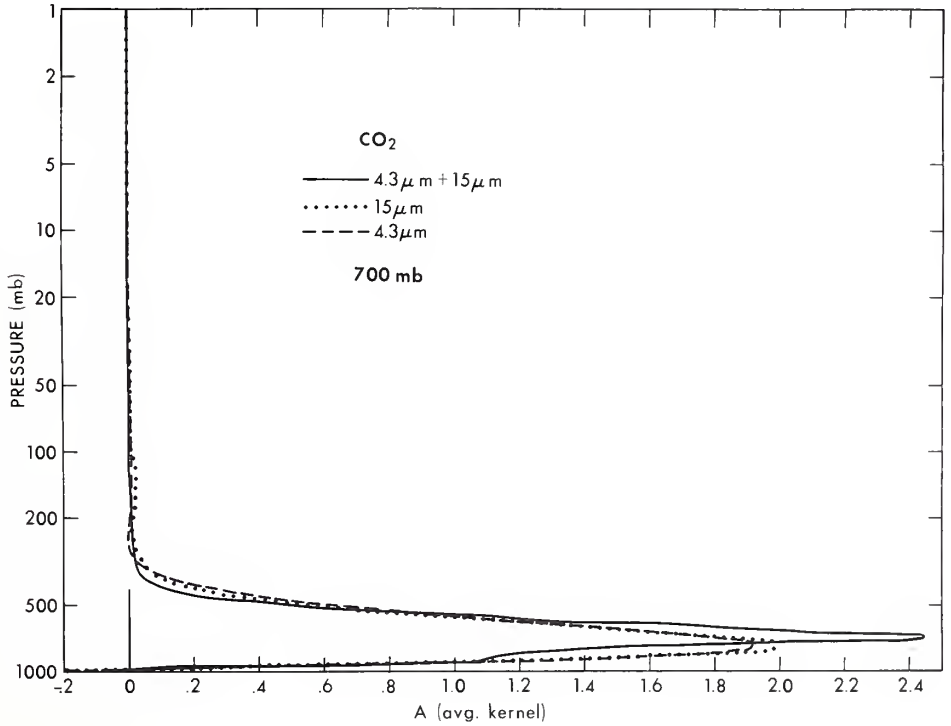

Figure 12.--*Averaging kernels at 700 mb for the 4.3-μm band, 15-μm band, and 4.3-μm + 15-μm bands plotted as functions of atmospheric pressure.*

three cases. Finally, the center and the resolving of A(x,x') for the above-mentioned three cases are computed and plotted in figures 13 and 14, respectively.

4. DISCUSSION

Qualitatively, the curves of figures 4 to 12 indicate that the 12 channels of the combined 4.3-μm and 15-μm CO_2 bands has better vertical resolution of temperature profiles than that of the 7 channels of the 15-μm band, uniformly for all p, which in turn has better vertical resolution than that of the 5 channels of the 4.3-μm band. This is substantiated by the center vs. p curves in figure 13 and the resolving length w(p) vs. p curves in figure 14. It is found that the addition of the 5 channels of the 4.3-μm band to the 15-μm band improves the resolving length of the averaging kernel for the 15-μm band alone about 1 to 15% in the troposphere, 15 to 43% in the stratosphere except in the range of 3.5 to 8.5 mb, and 15% at the tropopause. Note that the w(p) vs. p curve for the 15-μm band is comparable to that of Conrath (1971). Furthermore, figure 13 shows that in general the center of the averaging kernel for the combination of 4.3-μm and 15-μm bands is closer to the level to which the kernel pertained than the other two cases. This is particularly true in the upper stratosphere, for example in the layer of $p < 10$ mb. Although the resolving length of the 15-μm band is shorter than that of the combined 4.3-μm and 15-μm bands in the range of 3.5 to 8.5 mb, the large deviation of the center of the averaging kernel for the 15-μm band from the level to which the kernel pertains does away with any advantage of shorter resolving length. In our opinion, these facts indicate the uniform superiority of the combination of 4.3-μm and 15-μm bands over the other two cases for all p in the vertical resolution of temperature profiles.

Figure 14 indicates that the resolving length for the 4.3-μm CO_2 channels is poor in the range of 8 to 60 mb. This is mainly because of the lack of weight concentration of $K[x,\nu_i]$'s in that particular range (figure 4). Unfortunately, the method of Backus and Gilbert will not yield accurate results under this circumstance. To obtain more accurate results, one has to experiment with various J-functions other than that of eq (12).

It is known that the instrument noise will contaminate the above results (Backus and Gilbert, 1970). The general effect of the noise here is believed to be the same as that in the analysis of Conrath (1971).

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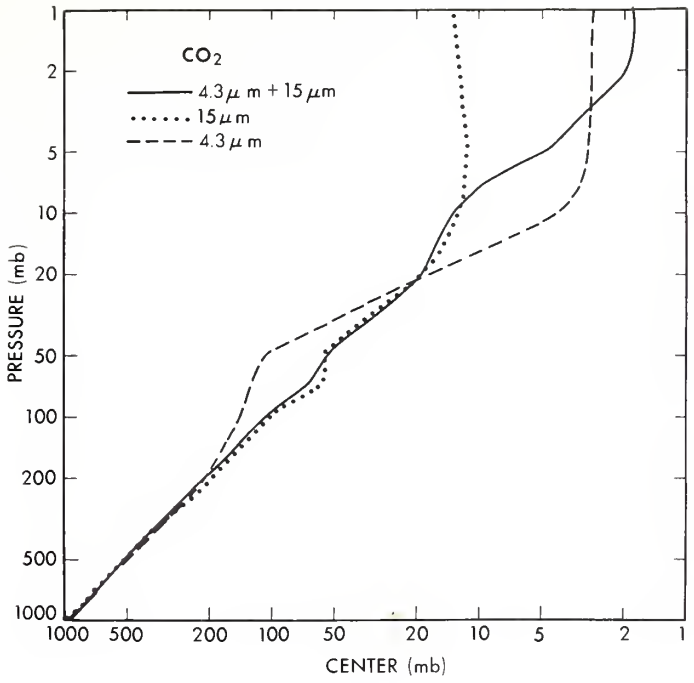

Figure 13.--*Averaging kernel center for the 4.3-μm band, 15-μm band, and 4.3-μm + 15-μm bands plotted as functions of atmospheric pressure.*

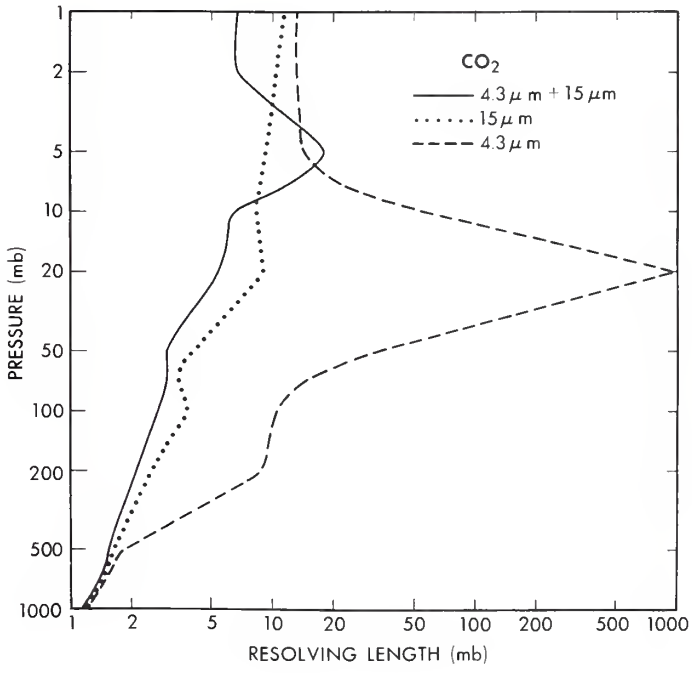

Figure 14.--*Resolving lengths for the 4.3-μm band, 15-μm band, and 4.3-μm + 15-μm bands plotted as functions of atmospheric pressure.*

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